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Strategic Planning of Regional Energy System Based on Life Cycle Assessment Methodology

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ABSTRACT

The Krasnodar territory is considered one of most attractive regions in Russia in terms of its climatic characteristics for the development of renewable energy sources. According to the current plans of Russian Ministry of Energy, the cumulative capacity of wind generating facilities in the Krasnodar Territory will reach 405 MW by 2022. It is well known from the literature, the average installed capacity utilization factor of wind turbines currently is about 30%. Comparatively low installed capacity utilization factor of wind parks significantly increases their payback period, thereby reducing commercial attractiveness. However, from an environmental point of view, low installed capacity utilization factor of wind plant can also be a problem: this means that most of the energy and materials spent on the manufacturing of an energy object do not produce a useful output, in other words, wasted. Therefore, a promising way to increase the installed capacity utilization factor of wind and solar plants is the use of energy storage systems. But the production and disposal of chemical energy storage systems is also associated with significant negative environmental effects, therefore, in the case of their large-scale application it is necessary to correctly assess the environmental consequences of this method of increasing the installed capacity utilization factor of wind plants. In this study we evaluate on the basis of the life cycle assessment methodology two possible alternatives: (1) the use of wind parks without energy storage systems, and (2) the production of energy storage systems necessary for the accumulation of electricity produced by wind parks in the Krasnodar Territory, which cannot be supplied to the power system and, hence, is thrown away.

Keywords: Wind Energy, Life Cycle Assessment, Regional Energy System, Energy Storage, Strategic Planning

JEL Classifications: O33, Q42, Q47, Q48

1. INTRODUCTION

The creation and successful operation of a system of state support for renewable energy in Russia on the basis of capacity supply agreements has led to the fact that an increasing number of Russian regions include the construction of solar and wind power plants in their strategies of economic development (Kozlova and Collan, 2016; Ratner and Nizhegorodtsev, 2017; Smeets, 2017). In many cases regional authorities consider renewable energy projects not so much as an opportunity to improve the region's energy supply, but as a good way to develop enterprises producing the necessary components of energy equipment, create new jobs and attract investment in the region,

which is consistent with global trends (Harper, 1993; Ratner and Klochkov, 2017; Azarova et al., 2019; Eitan et al., 2019). When making strategic decisions, the issues of choosing the type of power equipment, the methods of its production and operation are decided solely on the basis of economic parameters: specific capital costs, operating costs, profitability, payback period for a power plant construction project, etc. (Zaichenko and Shterenberg 2017; Butuzov et al., 2018; Ratner and Khrustalev, 2018; Kondrat'eva et al., 2019). The issues of environmental efficiency in this case, as a rule, are not considered, since it is believed that the use of renewable energy sources (RES) in itself automatically leads to an improvement in the environmental situation.

2. RESEARCH BACKGROUND AND TASKS

Indeed, the operation of renewable energy has significantly less negative impact on the environment than traditional hydrocarbon energy, however, the production of energy equipment for the use of renewable energy (solar photovoltaic panels, wind turbines, etc.) is a fairly energy-intensive and material-intensive process and produces its specific negative environmental effects (Amponsah et al., 2014; Nizhegorodtsev and Ratner, 2016; Li et al., 2018; Mendecka and Lombardi, 2019). Therefore, the environmental issues also must be borne in mind when making strategic decisions on the development of a particular type of renewable energy. Nowadays the approach to the analysis of promising areas of development of energy systems taking into account the assessment of the full product life cycle (LCA) including upstream activities has become extremely popular both in academic and business analytic literature. According to this approach generated electricity is understood as a product, and the best technology for its generation can be chosen. The life cycle assessment in this case is calculated at all stages - from the extraction and processing of raw materials to the delivery of finished products to the consumer, which fully corresponds to the approach enshrined in the international environmental management standards of ISO 14,000 series. Thus, among the studies of recent years, one can distinguish the study of Mendecka and Lombardi, who analyze environmental impact of on shore and offshore wind energy farms (Mendecka and Lombardi, 2019). Ratner and Lychev in their research compare the environmental performance of several modern photovoltaic technologies (Ratner and Lychev, 2019). Ritzen et al. studies how the method of installation of solar panel can decrease some negative environmental impacts (Ritzen et al., 2017). Besseau et al. investigate the evolution of LCA assessments of wind energy between 1980 and 2030 (Besseau et al., 2019). Moslehi and Reddy analyze with LCA the environmental impacts of campus power generation energy portfolio mix (Moslehi and Reddy, 2019). Paletto et al. study environmental effects of biomass power plants with LCA methodology (Paletto et al., 2019).

Using LCA approach significantly increases the validity of management decisions regarding the choice of the most attractive renewable energy technologies for development and government incentives. However, to date, the use of the methodology for analyzing and assessing the product life cycle in accordance with ISO 140040-14043 has been limited mostly to the tasks of choosing the most environmentally friendly (throughout the life cycle) from several competing technologies (Mendecka and Lombardi, 2019; Ratner and Lychev, 2019; Paletto et al., 2019). Only a few papers can be noted in which this methodology is used to compare alternative design options for the energy system (Tschiggerl et al., 2018; Moslehi and Reddy, 2019) or options for using a specific resource, for example, urban space (Corcelli et al., 2019).

In this article, we attempt to expand the scope of application of the LCA methodology to solve the problems of strategic planning for the development of the regional energy system as a whole by the example of the situation with planning the development of wind energy in the Krasnodar Territory in the South of Russia.

The Krasnodar Territory is considered the most attractive region in Russia in terms of its climatic characteristics for the development of RES, which can replace up to 22 GWh of thermal energy and 13 GWh of electric energy currently produced from hydrocarbon fuel. However, the total installed capacity of renewable energy facilities in the Krasnodar Territory currently stands at about 220 MWh. For the period 2011-2017 total electricity consumption in all areas of the Krasnodar Territory increased by 30% from 21,960 to 31,103 million kWh. In the period from 2010 to 2020, the total load on the power system of the Krasnodar Territory, according to experts, will increase from 3,541 MW to 7,100 MW, that is, more than doubled. Thus, the Krasnodar Territory has an unbalanced energy status, which is characterized by a high percentage (50-60%) of electricity imports and a frequent shortage of electricity. Calculations of the regional energy balance show that the average energy shortage is 22 GWh/year. Given this general growth dynamics, the construction of new renewable energy facilities in the region is considered promising.

According to the reports for 2016-2018, presented by Ministry of Energy of Russian Federation, in the Krasnodar Territory, as well as in the Republic of Adygea, it is planned to build generating facilities that operate on the basis of RES in relation to the following types of generating facilities (Table 1). The cumulative capacity of wind generating facilities in the Krasnodar Territory and the Republic of Adygea, selected according to the results of the tender, will reach by 2022 the number of 405 MW. The implementation of the projects will be handled by JSC VetroOGK (a subsidiary of Rosatom).

It is well known from the literature, the average installed capacity utilization factor of wind turbines currently is about 30% (GWEC, 2018; Child et al., 2018). Electricity generation varies depending on the season and time of day, a significant part of the generated energy cannot be supplied to the grid without its significant modernization (Ratner and Nizhegorodtsev, 2018). Comparatively low installed capacity utilization factor of wind and solar power facilities significantly increases their payback period, thereby reducing commercial attractiveness. However, from an environmental point of view, low installed capacity utilization factor of renewable energy plant can also be a problem: this means that most of the energy and materials spent on the manufacturing of an energy object do not produce a useful output, in other words, wasted. Therefore, a promising way to increase the installed capacity utilization factor of wind and solar plants is the use of energy storage systems (Child et al., 2018; Azzuni and Breyer, 2018). The energy storage system sets itself a number of tasks to ensure the quality and uninterrupted supply of electricity, as well as the ability to store during low consumption and use it to balance power.

In modern electrical engineering, various energy storage technologies are used. The storage system can be chemical or electrochemical, mechanical, electromagnetic and thermal, each of which includes various types of equipment (Amrouche et al., 2016; Nikolaidis and Poullikkas, 2017; Antipov et al., 2019).

Table 1: The list of selected renewable energy projects for implementation in the Krasnodar Territory and the Republic of Adygea

The name of the project	Location of the project	Planned start date	Planned capacity, MW
Shovgenovskaya Wind Farm, cycle 2018	Republic of Adygea	01.12.2018	150
Pilotnaya Wind Farm, cycle 2019	Krasnodar region	01.12.2019	20
Pilotnaya Wins Farm-67	Krasnodar region	01.12.2019	10
Pilotnaya Wind Farm, cycle 2020	Krasnodar region	01.12.2020	40
Vetropark 9 and10	Krasnodar region	01.12.2020	50
Vetropark-22	Krasnodar region	01.12.2021	35
Pilotnaya Wind Farm- 52	Krasnodar region	01.12.2021	20
Shovgenovskaya Wind Farm, cycle 2020	Republic of adygea	01.12.2022	20
Beregovaya wind farm	Krasnodar region	01.12.2022	20
Pilotnaya Wind Farm, 2018-4	Krasnodar region	01.12.2022	40

Chemical energy storage systems are the most variable, and most of them are subject to further research and development. The most common types of batteries currently are lithium-ion (Li-ion), lead-acid, sodium-sulfur (NaS), nickel-cadmium (NiCd), nickel-metal hydride (NiMH) and nickel-chloride batteries, also known as acronym ZEBRA. The production and disposal of chemical energy storage systems is associated with significant negative environmental effects (Li et al., 2014; Baumann et al., 2017; Arciniegas and Hittinger, 2018; Balducci et al., 2018). Therefore, in the case of their large-scale application for the accumulation and storage of excess energy generated by wind power plants, it is necessary to correctly assess the environmental consequences of this method of increasing the installed capacity utilization factor of wind plants.

In this study, we set ourselves the following research task: to evaluate, on the basis of the LCA methodology, and compare the environmental effects of two possible alternatives: (1) the use of wind parks without energy storage systems, and (2) the production of energy storage systems necessary for the accumulation of electricity produced by wind parks in the Krasnodar Territory and the Republic of Adygea, which cannot be supplied to the power system and, hence, is thrown away. Lost renewable energy in the second alternative must be replaced by traditional generation based on hydrocarbons. In case of Krasnodar Region and Republic of Adygea the traditional generation of electricity is based on natural gas.

3. METHODOLOGY

For numerical evaluation of environmental effects of batteries manufacturing and use as well as generation electricity on gas fueled power stations over the entire life cycle Ecoinvent data was used. The Ecoinvent database is an international life cycle assessment database of products and services in accordance with ISO 14040-14043 standards (Guinée et al., 2001). Ecoinvent provides a collection of primary data on the environmental impact of various stages of the product life cycle. The advantage of this approach (LCA) is the most complete relevance of the data, which are automatically recalculated according to the matrix method in the event of new information on environmental effects at any initial stage of the life cycle.

Life cycle impact assessment is carried out on the basis of one or several methods. Each of them differs from the other in the

Table 2: CML2001 environmental impact categories, selected for analysis, and their indicators

Impact category group	Name of the impact category in the method	Unit
Acidification	Acidification potential - average Europe	kg SO ₂ -Eq
Climate change	Climate change - GWP100	kg CO ₂ -Eq
Ecotoxicity	Freshwater aquatic ecotoxicity - FAETP100	kg 1,4-DCB-Eq
	Freshwater sedimental ecotoxicity - FSETP100	
	Marine aquatic ecotoxicity - MAETP100	
	Marine sedimental ecotoxicity - MSETP100	
Eutrophication	Eutrophication - average Europe	kg NO _x -Eq
Human toxicity	Human toxicity - HTP100	kg 1,4-DCB-Eq
	Human toxicity - HTP20	
	Human toxicity - HTP500	

Table 3: Battery specific energy

Specific energy, Wh/kg	Li-ion	ZEBRA (NaCl)	NiMH
Estimations from the literature	100-150	90-120	60-120
Estimations are taken for calculations	125	116	90

number of exposure categories that are included in this technique. For the analysis, we chose the most comprehensive method for environmental impact by the LCIA method "CML 2001," developed by the Center for Environmental Sciences of the University of Leiden (Guinée et al., 2001). The method is based on the LCA procedure in accordance with ISO 14000 standards. The results in this methodology are grouped into categories in accordance with general environmental mechanisms or generally accepted groupings (Guinée et al., 2001; Ratner and Lychev, 2019; Ratner et al., 2019). The most significant environmental impact categories selected by us, for which the assessments were carried out, are presented in Table 2.

Among the energy storage technologies, the most common rechargeable batteries were selected to assess the environmental effects. For each type of battery, all available data from the EcoInvent database was used. Calculation of effects was carried out on the mass of the produced product (kg), which was evaluated individually for each system. Through systematic observations and

Table 4: EcoInvent data for environmental load for most significant categories

Impact category and unit	Li-ion, 1 kg	NiMH, 1 kg	ZEBRA, 1 kg	Electricity, 1 kWh
Acidification potential, kg SO ₂ -Eq	0,1311	1,4301	0,619060	0,0005448
Climate change, kg CO ₂ -Eq	5,6515	18,9090	6,024600	0,41233
Eutrophication potential, kg NO _x -Eq	0,039083	0,09815	0,045731	0,000362
Freshwater aquatic ecotoxicity, kg 1,4-DCB-Eq	97,569	113,02	79,955000	0,0095274
Freshwater sediment ecotoxicity, kg 1,4-DCB-Eq	228,01	276,89	188,940000	0,021645
Human toxicity, kg 1,4-DCB-Eq	66,076	28,6660	35,861000	0,04335
Marine aquatic ecotoxicity, kg 1,4-DCB-Eq	325,67	389,73	272,940000	0,032968
Marine sediment ecotoxicity, kg 1,4-DCB-Eq	403,56	475,58	327,590000	0,038675

data collection, it was found that the average daily work of the wind farm in the regions of the planned construction is 15 h, i.e. potential average installed capacity utilization factor (subject to the use of all energy) can reach 60%. We assume that the energy storage system will increase the installed capacity utilization factor by 20% (lower estimate). In this case, energy storage systems should provide daily accumulation of the following amount of energy:

$$405 \text{ MW} * 24 \text{ hours} * 0.2 = 1944 \text{ MWh or } 1,944,000 \text{ kWh}$$

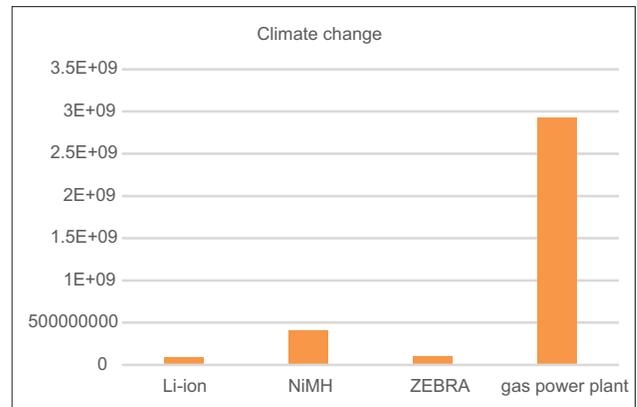
Using this number now we will calculate the required mass of batteries in order to provide all wind turbines in the region with systems for the accumulation and storage of excess energy, and to conduct a comparative assessment of environmental effects by impact categories. The calculation of the mass of energy storage systems was based on the specific energy consumption of the batteries (Table 3), i.e. the amount of energy that batteries can store. Table 3 is based on average ratings from commercial battery models. Batteries with improved characteristics, which are at the stages of prototypes and small-scale production, in this case were not taken into account.

Using the data in Table 3, we obtain the following estimates of the need for energy storage systems: for Li-ion batteries – 15,552,000 kg; for ZEBRA batteries – 21,600,000 kg; for NiMH batteries – 16,758,620 kg. Further, using the data of EcoInvent (version 2019) on the negative environmental impact of the production of 1 kg of batteries of each type and the data on the negative impact of the production of 1 kWh of electricity by the gas power plant (Table 4), we obtain the desired estimates that we can use to compare and choose an alternative way of organization of regional energy system. Here we assume that the life cycle of each type of battery is 10 years, then over 10 years it can be accumulated 7,095.600 GWh of electric energy, which otherwise would be lost and have to be additionally produced by a gas power station.

4. RESULTS AND DISCUSSION

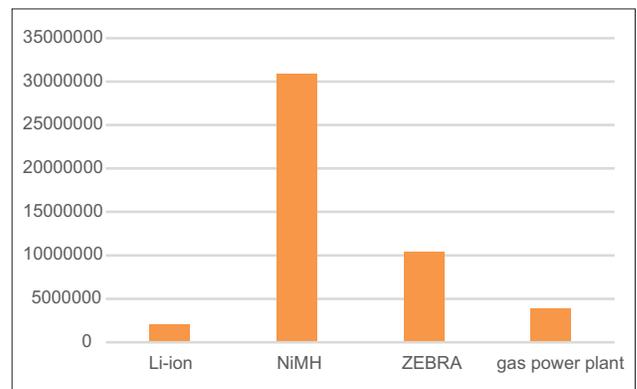
The results of a comparative analysis of the assessments of the negative impact of the considered alternative options for organizing a regional energy system for the selected categories are presented in Figures 1-4. In the category of “climate change,” the accumulation of excess electricity using any of the technically available energy storage systems is much more preferable than the operation of a wind park with a traditional installed capacity utilization factor. The non-use of the energy generated by the wind park and the replacement of the “lost” generation volumes even in the case of most environmentally friendly gas generation, leads

Figure 1: The estimations of greenhouse gas emissions (kg CO₂-Eq) for different regional energy system design options



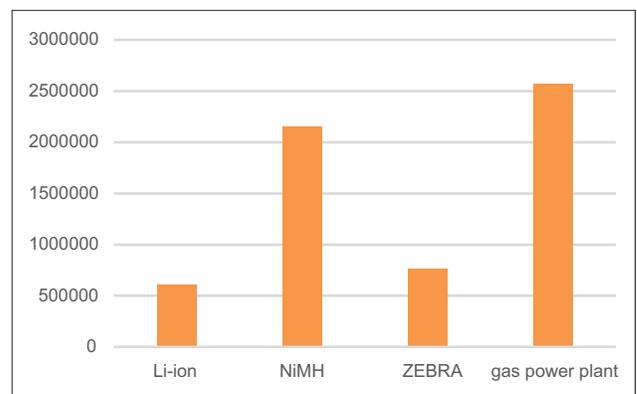
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Figure 2: The estimations of acidification potential (kg SO₂-Eq) for different regional energy system design options



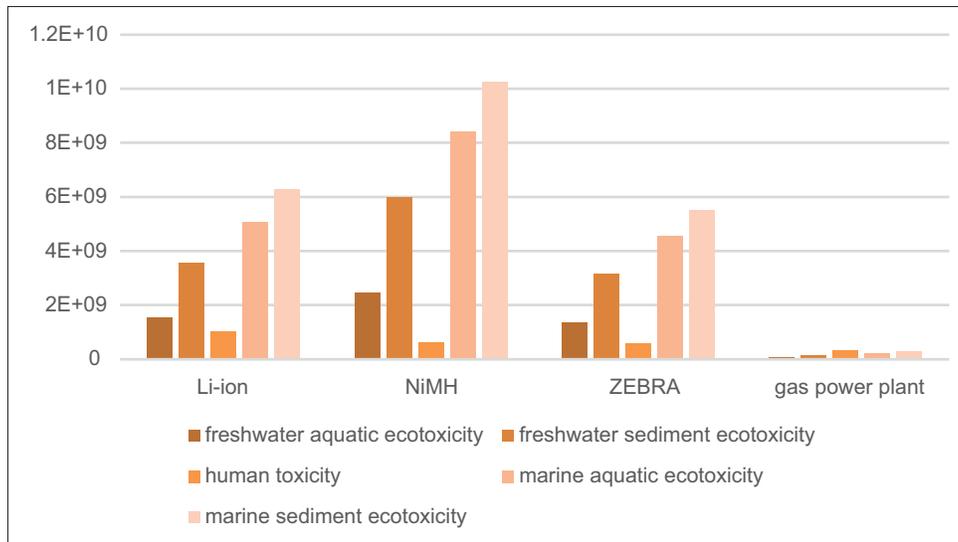
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Figure 3: The estimations of eutrophication potential (kg NO_x-Eq) for different regional energy system design options



Source: Authoring

Figure 4: The estimations of ecotoxicity (kg 1,4-DCB-Eq) for different regional energy system design options



Source: Authoring

to an increase in greenhouse gas emissions by at least 7 times, compared with the option to equip the wind park with energy storage systems.

In the category of “oxidation potential,” the least preferred option for organizing a regional energy system is to equip the wind park with an energy storage system based on nickel metal hydride batteries, the most preferred is to equip the wind park with lithium-ion energy storage systems. A simple discharge of generated extra energy and replacing its volumes with gas generation is also a fairly good option in terms of sulfur dioxide emissions.

In the category of “eutrophication potential,” the collection of excess energy generated by wind farms is the least preferred alternative, which leads to the highest emissions of NOx into the environment. The most preferred alternative in this category is equipping the wind park with lithium-ion batteries. The second preferred alternative is to equip wind farms with ZEBRA energy storage systems. Equipping wind farms with nickel-metal hydride batteries does not lead to a significant gain in the “eutrophication potential” category compared to the underutilization of the energy generated by wind farms.

In the ecotoxicity category, the most preferred option is the use of wind parks without energy storage systems and the replacement of “lost” volumes with conventional gas generation. Moreover, this preference remains for all five considered categories of ecotoxicity: freshwater and marine aquatic ecotoxicity, freshwater and marine sediment ecotoxicity, human ecotoxicity. The second preferred option for organizing the operation of wind parks is to equip them with ZEBRA energy storage systems. Lithium-ion batteries in all categories of ecotoxicity show slightly worse results than ZEBRA, and nickel metal hydride show much worse environmental impact indicators in all categories of ecotoxicity.

Thus, it is not possible to unambiguously determine the best option for organizing a regional energy system in terms of minimizing

negative environmental impacts. The option of equipping wind parks with energy storage systems based on lithium-ion batteries turns out to be the most preferable alternative in terms of climate impact, oxidation potential and eutrophication potential, however, it is significantly inferior to the option of generating additional volumes of electricity by gas generation in all categories of ecotoxicity. Therefore, the final decision on choosing the most environmentally preferable option for organizing the work of wind farms under construction must be made on the basis of the real environmental situation in the region and its most acute environmental problems.

If the goal of environmental policy is to reduce greenhouse gas emissions (for example, in the framework of fulfilling obligations under international climate agreements), then it makes sense to equip wind parks with energy storage systems, of which ZEBRA batteries and lithium-ion batteries are the best alternatives for most other impact environmental categories rather than nickel metal hydride batteries. If the goal of regional environmental policy is to reduce eco-toxicity (which is consistent with the real environmental situation in the Krasnodar Region as can be seen from the publications of Russian scientists (Ratner and Zaretskaya, 2018), then the refusal to equip wind farms with energy storage systems is a highly reasonable option for organizing a regional energy system.

5. CONCLUSIONS

Our study showed that currently available energy storage technologies provide clearly pronounced advantages in organizing a regional energy system as compared to simply dumping excess energy generated by renewable energy facilities only in terms of greenhouse gas emissions. In other categories of environmental impact, the advantage of the option of accumulating surplus energy is not so obvious, but in terms of toxicity this option is significantly worse than the option of operating wind parks without accumulating electricity. Therefore, when deciding on

the organization of a regional energy system, it is necessary to consider which category of environmental impact in the region is the most important.

Note that the above conclusions are valid for the case when the entire life cycle of electricity generation and the entire life cycle of energy storage systems are implemented on the territory of the same region. In reality, this is not entirely true. Currently, the production of energy storage systems is not developed in the Krasnodar Territory; moreover, the development of such industries is not provided for in the medium-term plans for the socio-economic development of the region. Therefore, equipping the wind parks under construction with energy storage systems imported into the region can be a reasonable way to solve the region's most acute environmental problems in the medium term. However, in general, this option is not preferred.

Another way to reduce the negative impact of energy storage systems on the environment is to equip wind farms with already used energy storage systems, for example, used electric car batteries. Such an alternative is now actively discussed in the technical literature. Assessment of the environmental effects of this option for organizing a regional transport and energy system is the subject of further research by the authors.

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